Final Scientific Report

National Aeronautics and Space Administration

Grant NSG-408

December 31, 1966

Part III: The Effects of Thermal Stresses on the Aerobic and Anaerobic Wcrk Capacities of Men

by

S. Robinson, B. Sadowski, and J. L. Newton

Department of Anatomy and Physiology.

Indiana University

Bloomington, Indiana

The effects of thermal stresses on the aerobic and anaerobic work capacities of men. S. Robinson, B. Sadowski and J. L. Newton. NASA NSG 408, December 31, 1966.

Abstract

The effects of hyperthermia and hypothermia on $\dot{V}_{O_2}$ max, O_2 debt, and the elevation of blood lactate of 4 men in exhausting work were determined. After appropriate preconditioning periods in control (24 C), hot and cold environments, each man ran on the treadmill at a rate selected to exhaust him in 3 to 6 minutes. The men started the runs in the control, heat, and cold experiments with mean body temperatures of 35.3, 38.1 and 33.3 C respectively, and corresponding thermal gradients from core to surface of 7.3, 2.7, and 10.1 C. The average times of running to exhaustion were 4.63, 3131 and 4.1 minutes respectively in the 3 experiments.

The reduced capacity for running in the heat was dependent on average reductions of 5% in $\dot{V}O_2$ max and 10% in O_2 debt, the latter associated with a reduction of 15% in blood lactate, as compared with values observed in the control runs. These changes in the heat were due to circulatory strain resulting from conflicting demands for circulation to the working muscles and for cutaneous circulation in heat transport. The O_2 requirement per minute of running time in the heat was unchanged from controls.

The reduced capacity for running in the cold was dependent on average reductions of 5% in $\dot{V}_{O_2}$ max and an increase of 6% in the O_2 requirement per minute of running time with no significant difference in average values of O_2 debt and lactate from values in control runs. The decreased efficiency in the cold probably resulted from increased tension and viscosity in the cold muscles, and the fact that a greater proportion of the energy involved in the work was derived from anaerobic sources than in the control runs.

The performance of work at maximal rates is limited by the aerobic and anaerobic capacities of the men and by the efficiency with which the work can be performed. U. S. astronauts in attempting to perform work outside the capsule while orbiting around the earth have found ordinary tasks to be exhausting. Their reduced capacity for performing external work in space could be the result of (a) reduced efficiency due to interference of the space suit with bodily movements, and/or to the conditions of leverage and anchorage associated with weightlessness; (b) reduced aerobic capacity resulting from reduced pO_2 in the air being respired, if it should occur, or from impaired ability to increase cardiac output and to make vasomotor adjustments required for O_2 transport to the working muscles, or (c) alterations of anaerobic capacity for work caused by weightlessness, thermal factors in the environment, or disturbances of water and electrolyte balance.

The interference of hot environments with temperature regulation of men in prolonged aerobic work on the earth is well understood (7-9); but few studies have been made of maximal working capacity of men under cold and heat stresses. Williams et al. (12) and Rowell et al. (11) found little reduction in the aerobic capacities of men in exhausting work of short duration in the heat, but a substantial decrease in their endurance.

The present study was made in an attempt to determine whether or not the thermal state of the body may affect the aerobic and anaerobic capacities and the endurance of men in exhausting work.

PROCEDURE

Four men, ages 21 to 24, were used as subjects in this study. The characteristics of the men are given in Table 1. Three of them were subjects in O_2 debt experiments performed in each of three thermal states, i.e., cold, control, (comfortable), and hot. The fourth man was

Table 1. Physical characteristics and work rates of the subjects. Work rates in the exhausting runs were selected according to the men's abilities. Work rates in recovery were individually selected to raise V_{O_2} to about 50% of maximal rates.

Subj.	Age	Ht.	Wt.	B.S.	Run		Recovery work	
	yr	cm	kg	m^2	km/hr	%gr	km/hr	%gr
AC	23	181	74.2	1.95	17.7	6	10.5	0
DC	21	187	73.5	2.00	12.9	7	6.4	7
DL	24	185	67.4	1.90	12.9	8	6.4	8
GF	23	175	78.9	1.95	10.3	9	5.6	9

a subject in the control and hot experiments only. In the month preceding the study the men were subjects in a number of practice runs on the treadmill to acquaint them with all procedures. Their maximal O_2 consumptions ($\dot{V}O_2$ max) and the speeds and grades of the treadmill required to exhaust them in 4 to 6 minutes were determined in these runs.

The men wore shorts, tennis shoes, and socks in all of the O_2 debt experiments. Their skin temperatures were continuously recorded by thermocouples located on the index finger pad, arm, shoulder, back, abdomen, and thigh, and rectal temperature was continuously recorded by a thermocouple inserted to a depth of 7.5 cm. Respiratory exchange was determined by the open circuit method during an exhausting run on the treadmill and recovery in each experiment. The O_2 debts of the men following these runs were determined according to the exercise-recovery technique used in an earlier phase of this study (4). Lactate was determined by the enzyme method (8) on blood samples collected from an arm vein before the run and at approximately 1, 5, 10, 20, 35, 51, and 86 minutes of recovery following the run.

In all runs and recoveries of these O_2 debt experiments the following procedure was followed to determine respiratory exchange. The subject breathed outside air through a low resistance respiratory valve. In the run his expired air was passed from the valve through rubber tubing (3.8 cm. in diameter) into a mixing chamber and from this through a precision dry gas meter. Volumes of expired air through the meter were read and samples for analysis were collected from the mixing chamber at a uniform rate during each of the following periods of the run: 0-½, ½-1, 1-2, 2-3 minutes and so on until the subject reached exhaustion and stopped running. With the subject continuing to breathe through the system the treadmill was slowed down to an aerobic work rate previously found to require approximately 50% of the subject's $\dot{V}_{O_2}$ max. Five seconds after stopping the exhausting work he resumed work at the slower rate. His respiratory exchange was determined for the periods 10 sec. to 1 min, 1-3 and 3-5 minutes of the aerobic exercise-recovery by the same procedure used during the run. Thereafter, he continued the aerobic work and respiratory exchange was determined by collecting and measuring expired air in a Tissot spirometer during the following periods: 7-10, 13-16, 20-23, 26-29, 32-35, 38-41 and 44-47 minutes of the exercise recovery. The spirometer was flushed 3 times with his expired air before each of these collections. At 47 minutes a valve was turned to divert his expired air back through the mixing chamber and gas meter. At 50 minutes after the run the aerobic work was stopped and the subject sat quietly on a chair, continuing to breathe through the same system, and respiratory exchange was determined from 0-1, 1-3, 3-5 minutes of the rest recovery by the same procedure as in the first 5 minutes of the exercise recovery. He then reclined on a cot at the side of the treadmill and respiratory exchange was determined by collections in the Tissot from 7-10, 13-16, 20-25 and 30-35 minutes following the aerobic work. The relief periods from the mouth-piece and nose-clip between the collections during both the exercise and rest phases of the recovery made the subject more comfortable and relaxed. Values of oxygen consumed in the relief periods were calculated from rates estimated from curves plotted of the determined rates during recovery. All expired air samples for analysis were collected in 50 ml syringes sealed with ethylene glycol, and the analyses were made on the Haldane analyzer.

The O_2 debt in the exercise-recovery has two components, one measured during the aerobic work performed in the first 50 minutes of recovery, the second during the 35 minutes of rest following the aerobic work. In the exercise recovery the O_2 debt is equal to the excess O_2

consumed in the recovery period above the O_2 requirement for the aerobic work at the first constant rate attained during the recovery. In the rest recovery the O_2 debt is equal to the total O_2 consumed during the recovery period less the subjects O_2 requirement at the first constant rate attained during recovery. O_2 consumption usually returned to the steady state level required for the aerobic work within 35 minutes, and to a constant level in the rest recovery within 20 minutes.

The control experiments were performed on the subjects in a comfortable environment (24 C db, 15 C wb, air movement 55 meters/min). With body temperatures being recorded 3 of the subjects warmed up by walking on the treadmill at 5.6 km/hr, 2.5% gr (MR 190 Cal/m^2/hr) for 30 minutes before starting the run. The 4th man (DL) warmed up by walking for 15 minutes at 6.4 km/hr, 5.6% gr (MR 250 Cal/m^2/hr). After warming up each man rested for 10 to 15 minutes before starting his exhausting run at the speed and grade previously found to exhaust him in 4 to 6 minutes. Respiratory exchange and blood lactate changes were followed during the run and the exercise and rest phases of recovery as described above.

The heat experiments differed from the control experiments in that the subjects first walked on the treadmill (MR 240-260 Cal/m^2/hr) until they were near heat exhaustion with high rectal and skin temperatures and heart rates. Two of the men (AC and DL) worked in humid heat (36 C db, 33.5 C wb) and the other two (DC and GF) were exposed to dry heat (50 C db, 27 C wb). After the work they rested in the heat for 15 to 30 minutes and then performed an exhausting run on the treadmill. At the end of the run the thermostats were immediately turned down and the room air was cooled within 8 minutes to the control level (24 C db, 15 C wb) and the exercise and rest phases of recovery were carried out in the cool room as described above.

In the cold experiments the subjects, wearing only shorts, reclined on a saran net lounging chair for 60 to 75 minutes in a room temperature of 16.5 C, or until they were throughly chilled with rectal and mean skin temperatures averaging 36.8 and 26.8°C respectively. They then walked on the treadmill at a MR of 160 Cal/m^2/hr for 5 minutes and rested another 10 minutes before performing the exhausting run in the cold. At the end of the run the thermostats were turned up to 24 C db, 15 C wb, and recovery was carried out at the control temperature. We originally attempted to chill two of the nude subjects in a room temperature of 10 C, but found that they soon began to shiver violently and their rectal temperatures rose during a 1-hour exposure. Therefore it was decided to cool them at 16.5 C in which shivering was delayed for about an hour and their rectal temperatures tended to decline instead of rising.

The following symbols are used in this paper. "$\dot{V}_{O_2}$" means the rate of O_2 consumption, and "$\dot{V}_{O_2}$max" means maximal rate of O_2 consumption. T_r T_s and T_m are used to represent rectal, mean skin and mean body temperatures respectively. Mean body temperature was calculated according to Burton (3). db and wb represent dry bulb and wet bulb air temperatures respectively.

RESULTS

The rectal and mean skin temperatures of subject DL in the control, heat, and cold experiments are compared in detail in figure 1. This figure also serves to illustrate in general the sequence of events in the experiments. Temperatures of all four subjects in the runs and recoveries are shown in Table 2. Special attention is called to mean skin (T_s), rectal (T_r), and mean body (T_m), and to temperature gradients (T_r-T_s) during the actual runs, since evaluation of the effects of variations in body temperature on metabolic responses of the men in these exhausting runs is the purpose of this study. At the start of the run in the heat the gradients were small (2.3 to 3.6°C), indicating general cutaneous

Fig. 1. Rectal and mean skin temperatures of subject DL during the heat, control and cold experiments. Room temperatures and work periods are indicated: "W" or walk periods of walking, "R" for the exhausting runs. In all recoveries the room temperature was comfortable (24°C) and the subject walked (MR 250 Cal/m^2/hr) for 50 minutes and then rested for 35 minutes.

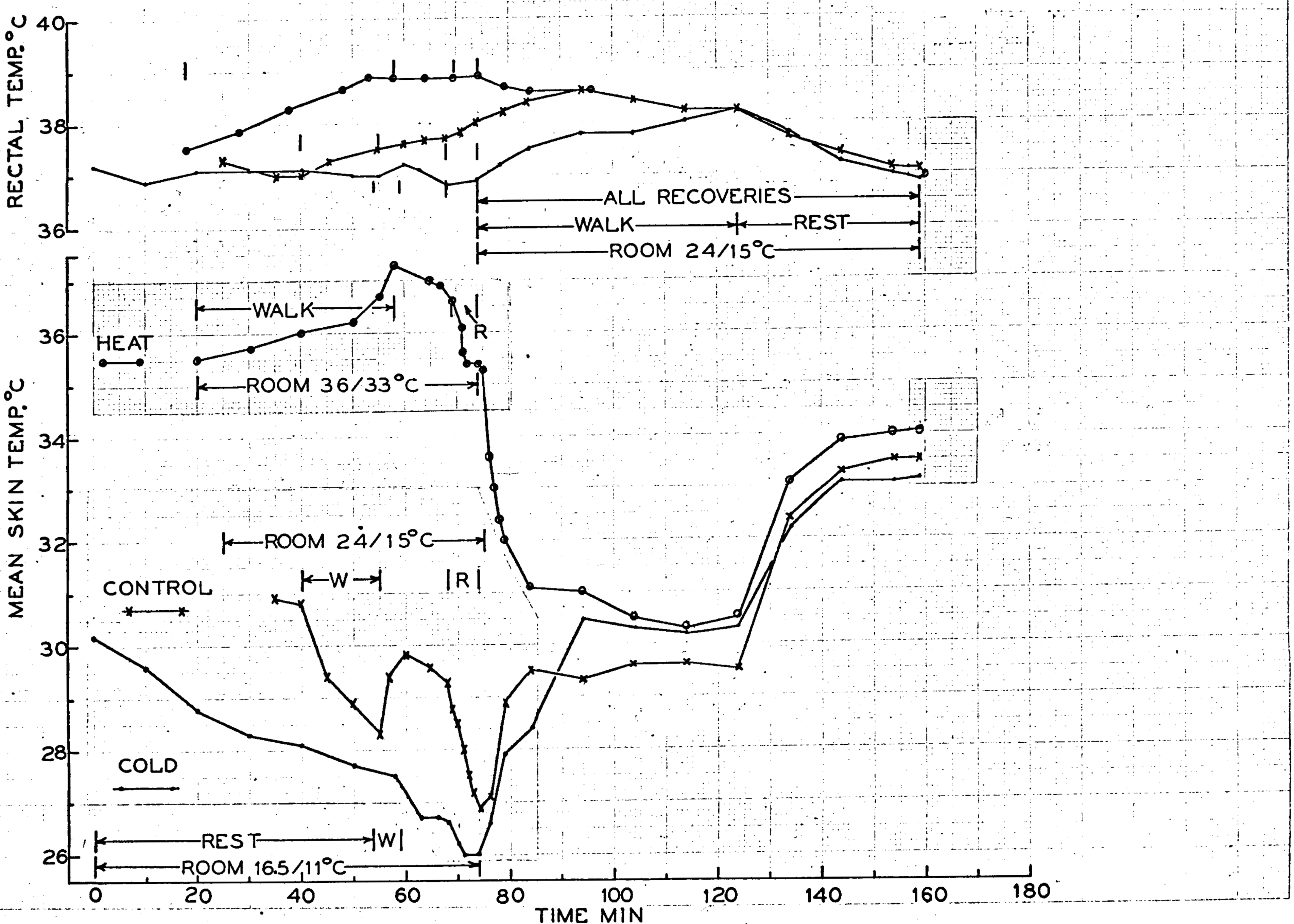


Table 2. Body temperatures of the men during the experiments. Symbols T_r, T_s, and T_m are the men's rectal, skin, and mean body (3) temperatures respectively; db and wb are the dry and wet bulb temperatures of the room.

	Subject AC						Subject DL						All subjects			
	Room, °C		Body temp. C				Room, °C		Body temp. C				Average values			
	db	wb	T_r	T_s	T_m	T_r-T_s	db	wb	T_r	T_s	T_m	T_r-T_s	T_r	T_s	T_m	T_r-T_s
CONTROL EXP. End walk	24.8	15.0	37.7	32.2	35.8	5.5	24.0	15.0	37.6	28.3	34.3	9.3				
Start run	25.0	15.0	38.0	32.5	36.1	5.5	24.0	15.0	37.7	29.3	34.8	8.4				
End run	25.0	15.0	38.1	30.8	35.5	7.3	24.0	15.0	38.0	26.9	34.1	11.1				
Recovery work, 10 min	25.0	15.0	38.5	32.1	36.3	6.4	24.0	15.0	38.4	29.5	35.3	8.9				
Work, 50 min	25.0	15.0	38.6	32.5	36.5	6.1	24.0	15.0	38.2	29.6	35.2	8.6				
Rest, 10 min	25.0	15.0	38.4	33.9	36.8	4.5	24.0	15.0	37.7	32.4	35.9	5.3				
Rest, 35 min	25.0	15.0	37.7	34.2	36.5	3.5	24.0	15.0	37.0	33.5	35.4	3.5				
HEAT EXP. End walk	36.0	34.0	39.0	37.8	38.6	1.2	36.0	33.0	38.9	38.3	38.3	1.6				
Start run	36.0	30.0	38.7	36.3	37.9	2.4	36.0	33.0	38.9	36.6	38.1	2.3				
End run	36.0	30.0	38.7	34.7	37.3	4.0	36.0	32.8	38.9	35.4	37.7	3.5				
Recovery work, 10 min	24.0	15.0	39.0	31.4	36.3	7.6	24.0	15.0	38.6	31.1	36.0	7.5				
Work, 50 min	24.0	15.0	39.0	30.3	36.0	8.7	24.0	15.0	38.2	30.5	35.5	8.1				
Rest, 10 min	24.0	15.0	38.5	33.4	36.7	5.1	24.0	15.0	37.8	33.1	36.2	4.7				
Rest, 35 min	24.0	15.0	37.7	34.3	36.5	3.4	24.0	15.0	36.8	34.0	35.7	2.8				
COLD EXP. End rest	16.8	8.5	36.3	28.9	33.7	7.4	16.5	12.0	37.0	27.5	33.7	9.5				
Start run	16.8	8.5	36.9	28.3	33.9	8.6	16.5	12.0	36.8	26.6	33.2	10.2				
End run	16.8	8.5	36.8	27.6	33.7	9.3	16.5	12.0	36.9	26.0	33.1	10.9				
Recovery work, 10 min	24.0	15.0	37.5	32.0	35.6	5.5	24.0	15.0	37.5	28.4	34.3	9.1				
Work, 50 min	24.0	15.0	37.5	31.6	35.4	5.9	24.0	15.0	38.2	30.3	35.4	7.9				
Rest, 10 min	24.0	15.0	37.4	33.2	35.9	4.2	24.0	15.0	37.8	32.2	35.8	5.6				
Rest, 35 min	24.0	15.0	37.0	34.6	36.2	2.4	24.0	15.0	36.8	33.1	35.5	3.7				

cont'd.

Table 2 (cont'd)

		Subject DC						Subject GF						All subjects			
		Room, °C		Body temp. C				Room, °C		Body temp. C				Average values			
		db	wb	T_r	T_s	T_m	T_r-T_s	db	wb	T_r	T_s	T_m	T_r-T_s	T_r	T_s	T_m	T_r-T_s
CONTROL EXP.	End walk	24.0	15.0	37.8	30.2	35.1	7.6	24.0	15.0	37.9	30.7	35.4	7.2	37.8	30.4	35.2	7.4
	Start run	24.0	15.0	37.7	29.4	34.8	8.3	24.0	15.0	37.9	30.8	35.4	7.1	37.8	30.5	35.3	7.3
	End run	24.0	15.0	38.0	27.0	34.2	11.0	24.0	15.0	37.9	28.7	34.7	9.2	38.0	28.4	35.6	9.7
	Recovery work, 10 min	24.0	15.0	38.3	29.0	35.0	9.3	24.0	15.0	38.2	30.2	35.4	8.0	38.1	30.2	35.5	8.2
	Work, 50 min	24.0	15.0	38.6	28.6	35.1	10.0	24.0	15.0	38.5	31.3	36.0	7.2	38.5	30.5	35.6	8.0
	Rest, 10 min	24.0	15.0	38.1	31.5	35.8	6.6	24.0	15.0	38.3	32.4	36.2	5.9	38.4	32.6	36.2	5.6
	Rest, 35 min	24.0	15.0	37.3	32.8	35.7	4.5	24.0	15.0	36.8	34.0	35.8	2.8	37.2	33.6	35.9	3.6
HEAT EXP.	End walk	49.8	27.0	39.5	36.7	38.5	2.8	50.0	27.0	39.0	37.1	38.3	1.9	39.1	37.2	38.4	1.9
	Start run	50.0	27.0	39.2	35.6	37.9	3.6	50.0	26.9	39.2	36.6	38.3	2.6	39.0	36.3	38.1	2.7
	End run	50.0	27.0	39.2	35.6	37.9	3.6	50.0	26.9	39.2	35.4	37.9	3.8	39.0	35.3	37.7	3.7
	Recovery work, 10 min	24.0	15.0	39.4	32.9	37.1	6.5	24.0	15.0	39.2	33.2	37.1	6.0	39.1	32.2	36.6	6.9
	Work, 50 min	24.0	15.0	39.4	30.5	36.3	8.9	24.0	15.0	39.8	31.3	36.8	8.5	39.1	30.7	36.2	8.6
	Rest, 10 min	24.0	15.0	39.1	32.3	36.7	6.8	24.0	15.0	39.6	33.0	37.3	6.6	38.8	33.0	36.7	5.8
	Rest, 35 min	24.0	15.0	37.7	34.0	36.4	3.7	24.0	15.0	37.8	34.6	36.7	3.2	37.5	34.2	36.4	3.3
COLD EXP.	End rest	16.0	10.2	37.1	26.6	33.4	10.5							38.6	27.7	33.6	9.1
	Start run	16.0	10.0	36.9	25.5	32.9	11.4							36.9	26.8	33.3	10.1
	End run	16.0	10.0	37.1	23.7	32.4	13.4							37.0	25.8	33.1	11.2
	Recovery work, 10 min	24.0	15.0	37.6	27.6	34.1	10.0							37.5	29.3	34.7	8.2
	Work, 50 min	24.0	15.0	38.9	29.2	35.5	9.7							38.2	30.4	35.4	7.8
	Rest, 10 min	24.0	15.0	38.5	32.2	36.3	6.3							37.9	32.5	36.0	5.4
	Rest, 35 min	24.0	15.0	37.7	33.1	36.1	4.6							37.2	33.6	35.9	3.6

vasodilation, and in the cold they were large (8.6 to 11.4°C) indicating marked peripheral vasocoustriction (Table 2). There was a drop in skin temperature and an increase in the gradient during each of the runs of subject DL (figure 1) and similar changes were shown by the other subjects (Table 2). The mean body temperature of the four men at the beginning of the exhausting runs in the control and heat experiments averaged 35.3 and 38.1°C respectively; corresponding mean values of the three subjects in the control and cold experiments were 35.2 and 33.3°C (Table 4). Since all recoveries were in comfortable conditions (24 db, 15 wb) the men's skin temperatures quickly returned to the comfort zone (29 to 32.5 C) during the exercise phase (0-50 min), and 32 to 34.6°C during the resting phase (50 to 85 min) of recovery. Rectal temperatures ranged from 38.2 to 39.6 at the end of the exercise phase and declined gradually during the following rest phase of recovery (figure 1 and Table 2).

Endurance in the exhausting runs is indicated by the time the men were able to continue the runs before exhaustion. The time of running was substantially reduced in all 4 men in the heat experiments as compared with the controls; while in the cold experiments it was reduced in two of the three subjects and unchanged in the third (Tables 3 and 4).

The oxygen consumptions, oxygen debts, and blood lactates of subject DL during the three exhausting runs and recoveries are shown in figure 2. The time relations of these responses in the other three subjects were all similar to those of DL and data on all four men are given in Table 3 and summarized in Table 4. In the heat experiments, average values of $\dot{V}_{O_2}$ max, O_2 debt and blood lactate were all somewhat lower than in the control experiments. In the cold $\dot{V}_{O_2}$ max was slightly reduced, but the total O_2 debts and the elevations of blood lactate in the runs were about the same as control values. Since the time of running was reduced in the cold the rates of accumulating the O_2 debt and of

Table 3. Metabolic adjustments of men in exhausting runs and recoveries in control, heat and cold experiments. The O_2 debt following the run is the sum of excess O_2 consumed during the exercise phase of recovery plus the O_2 debt in the resting phase.

$$O_2 \text{ requirement in liters/min} = \frac{O_2 \text{ consumed in run} + O_2 \text{ debt}}{\text{time of run in min}}$$

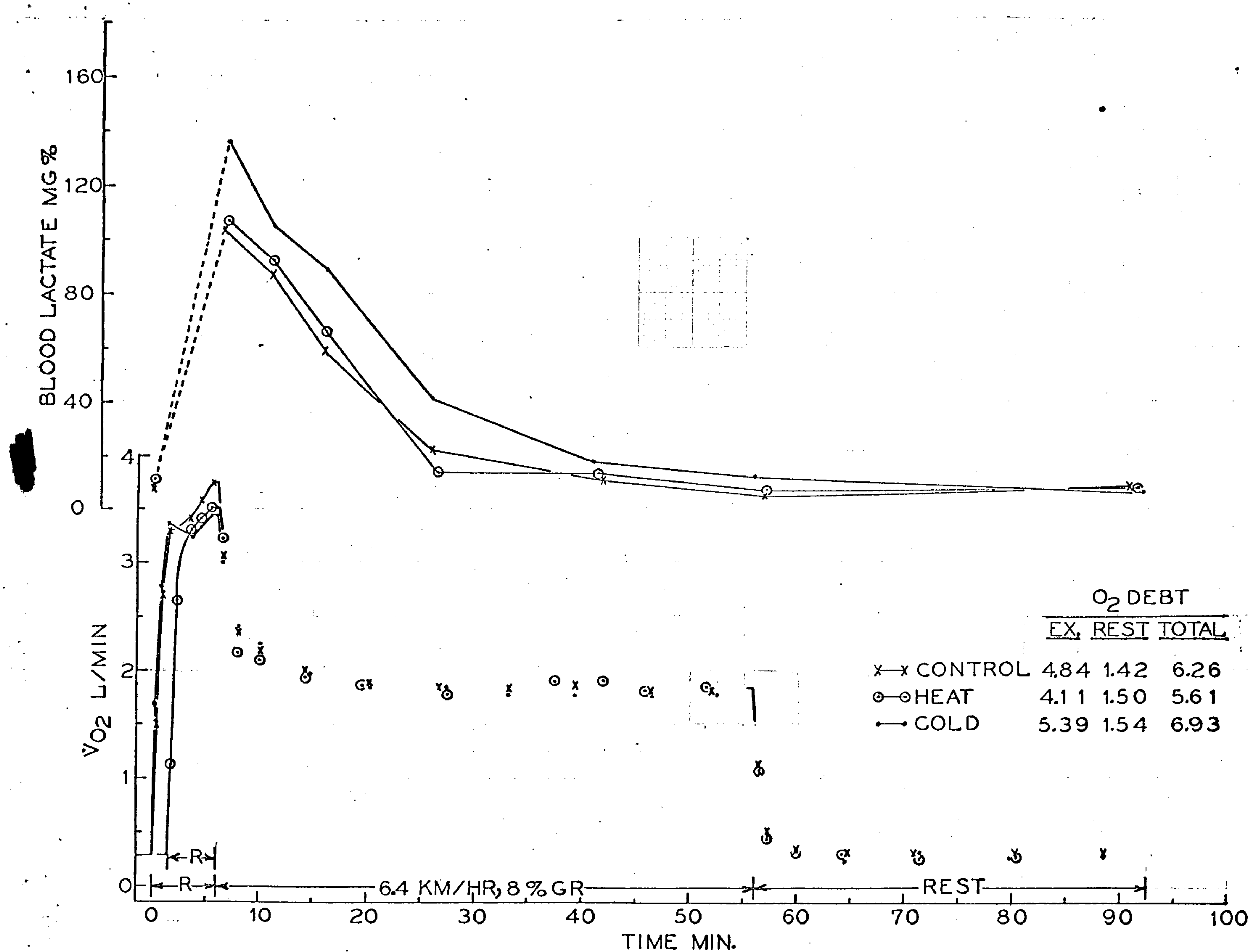
Subject	AC			DL			DC			GF		
		Recovery			Recovery			Recovery			Recovery	
	Run	Work	Rest	Run	Work	Rest	Run	Work	Rest	Run	Work	Rest
CONTROL EXPERIMENT												
Time, min	4.0	50	35	6.0	50	35	4.5	50	35	4.0	50	35
$\dot{V}_{O_2}$ liters/min	4.42	2.28	0.28	3.56	1.82	0.30	3.48	1.86	0.27	3.38	2.03	0.29
O_2 cons., liters	15.12			19.42			14.22			11.44		
O_2 debt, liters	10.2	8.1	2.1	6.26	4.84	1.42	7.75	5.74	2.01	6.39	5.0	1.39
O_2 req., liters/min	6.33			4.28			4.88			4.46		
Lactate, mg%	169.4	13.6	11.5	103.4	4.3	7.9	105.1	10.7	12.0	120.8	7.0	7.2
HEAT EXPERIMENT												
Time, min	3.0	50	35	4.5	50	35	3.5	50	35	2.3	50	35
$\dot{V}_{O_2}$ liters/min	4.05	2.25	0.28	3.41	1.80	0.27	3.27	1.88	0.31	3.29	2.15	0.30
O_2 cons., liters	9.90			13.51			10.11			5.93		
O_2 debt, liters	9.2	7.2	2.0	5.61	4.11	1.50	6.39	4.60	1.79	6.33	4.40	1.93
O_2 req., liters/min	6.37			4.25			4.72			5.45		
Lactate, mg%	143.6	7.6	8.5	107.4	7.3	7.7	77.6	10.9	11.3	97.4	8.3	9.1
COLD EXPERIMENT												
Time, min	2.8	50	35	6.0	50	35	3.5	50	35			
$\dot{V}_{O_2}$ liters/min	4.26	2.28	0.27	3.31	1.73	0.28	3.36	1.83	0.27			
O_2 cons., liters	10.43			18.86			10.75					
O_2 debt, liters	9.8	6.9	2.9	6.93	5.39	1.54	7.99	6.19	1.80			
O_2 req., liters/min	7.2			4.28			5.16					
Lactate, mg%	117.6	2.2	12.9	136.3	12.1	5.1	115.3	13.9	12.0			

[redacted]

Table 4. Summary of metabolic adjustments of men in exhausting runs and recoveries. T_m is mean body temperature (3). %Δ is the percent difference between the control values and those in the heat and cold experiments respectively. O_2 req. is defined in Table 3.

Subject	Time of run in min					T_m C at start of run				
	Control	Heat	%Δ	Cold	%Δ	Control	Heat	%Δ	Cold	%Δ
AC	4.0	3.0	-25	2.8	-30	36.1	37.9		33.9	
DL	6.0	4.5	-25	6.0	-30	34.8	38.1		33.2	
DC	4.5	3.5	-22	3.5	-22	34.8	37.9		32.9	
mean 3	4.83	3.67	-24	4.1	-15	35.2	38.0		33.3	
GF	4.0	2.25	-44			35.4	38.3			
mean 4	4.63	3.31	-29			35.3	38.1			
	$\dot{V}_{O_2}$ max, liters/min					Total O_2 debt, liters				
AC	4.42	4.05	-9	4.26	-4	10.2	9.2	-10	9.8	-4
DL	3.56	3.41	-4	3.31	-7	6.3	5.6	-11	6.9	+10
DC	3.48	3.27	-6	3.36	-3	7.8	6.4	-18	8.0	+3
mean 3	3.82	3.58	-6	3.64	-5	8.1	7.1	-13	8.2	+2
GF	3.38	3.29	-3			6.4	6.3	-16		
mean 4	3.71	3.51	-5			7.7	6.9	-10		
	O_2 req., liters/min					Blood lactate, mg%				
AC	6.3	6.4	+2	7.2	+14	169.4	143.6	-15	117.6	-31
DL	4.3	4.3	0	4.3	0	103.4	107.4	+4	136.3	+32
DC	4.9	4.7	-4	5.4	+1	105.1	77.6	-26	115.3	+10
mean 3	5.2	5.1	-2	5.6	+[illegible]	12 .9	109.5	-15	123.1	-5
GF	4.5	5.4	+20			120.8	97.4	-19		
mean 4	5.0	5.2	+4			124.7	106.5	-14		

Fig. 2 Changes of blood lactate and $\dot{V}O_2$ of subject DL during exhausting runs (R), exercise recoveries (6.4 km/hr, 8% gr), and rest recoveries.



raising the blood lactate in the runs were substantially higher than in the control experiments.

DISCUSSION

The reduced capacity for running in the heat as compared with the control experiments was dependent on reductions in both the aerobic and anaerobic energy available for the exhausting runs. The men showed small but consistant reductions of $\dot{V}_{O_2}$ max in the heat (mean 5%; range 3-8%). Their total O_2 debts following the runs averaged 10% less in the heat than in the control experiments. This reduction in maximal O_2 debt in the heat was associated with lower blood lactate concentrations accumulated during the runs; average values in blood samples collected 1 to 5 minutes after the runs were 109.5 mg% in the heat and 128.9 mg% in the control experiments. Taking into account both the total O_2 consumed during the runs and the O_2 debts determined in recovery the O_2 requirements in liters per minute of running time were calculated (Tables 3 and 4). Values of O_2 requirements in the runs were about the same in the heat and control experiments, and therefore the men's efficiencies in the runs were not changed by the heat. This is not unexpected since the mens' core temperatures in these runs were no higher than we have previously observed in champion runners in races lasting 15 to 30 minutes in air temperatures of 10 to 20 C (5).

Williams et al (2) and Rowell et al (1) have reported no significant effects of heat exposure on $\dot{V}_{O_2}$ max, or on the elevation of blood lactate in men performing exhausting work of short duration. The reductions of $\dot{V}_{O_2}$ max shown by our subjects in the heat were small but consistant. The differences between the above workers' results and ours is probably in the thermal state and degree of circulatory strain of the men at the time of the runs. The warming up work of our men before the run in the heat was harder (MR 250 Cal/m^2/hr) and continued for a longer time than theirs.

Our subjects were near heat exhaustion, with symptoms of syncope, high heart rates, and narrow gradients between core and surface temperature when they started the runs. They drank water to maintain water balance during the warm-up periods of the experiments in the heat and therefore dehydration was not a factor in producing the extreme circulatory strain and reduced work capacity. At the time they stopped the warm-up work they all had to recline for 10 to 15 minutes in the heat to recover before starting the runs. In the experiment on subject AC it was necessary to drop the wet bulb temperature of the room from 34.0 to 30.0 C for 15 minutes during his rest period and allow his skin temperature to fall from 37.8 to 36.3, before he was able to start the run. In all of the men skin temperatures fell sharply and symptoms of syncope disappeared during the runs in the heat, indicating increased evaporative cooling of the skin and rapid cutaneous vasoconstriction in response to the demand for circulation to the working muscles. The improved condition of the men during the runs in the heat was probably due to increased arterial pressure resulting from (a) vasoconstriction in the vascular beds of the skin and abdominal viscera, and (b) increased cardiac output resulting from increased venous return which was facilitated by the massaging action of the skeletal muscles on the veins and greatly increased respiratory movements during the work. The rapid drop of wet and dry bulb temperatures of the room at the beginning of the exercise-recovery rapidly lowered the men's skin temperatures, improved their circulatory condition, and made them comfortable.

The data show that the reduced capacity for running in the cold environment was dependent on an average reduction of 5% in $\dot{V}_{O2}$ max and an increase of 6% in the O_2 requirement/min of running time as compared with values observed in the control experiments (Tables 3 and 4). Although the actual O_2 debts accumulated in the runs were not significantly

[redacted]

increased, the average rate of accumulating the O_2 debt was increased from 1.67 liters/min in the control experiments to 2.0 liters/min in the cold. This was dependent on the fact that two of the men reached exhaustion more rapidly in the runs performed in the cold, and the man whose running time was not reduced in the cold accumulated a higher O_2 debt than in the control run. Similarly the average rate of accumulating lactate during the runs was higher in the cold (30 mg%/min) than in the control experiment (26.7 mg%/min). The small reductions in $\dot{V}_{O_2}$ max which occured in all three subjects in the cold was probably dependent on a decrease in the rate of O_2 utilization by cold muscles and possibly also on more sluggish transport of O_2 by the circulation. We have previously found the deep temperature of nude men's gastrocnemius muscles to be 32 to 33 C after an hour of rest in an air temperature of 16.5 C and in some men gastrocnemius temperature was 33 C after 90 minutes of rest in a room temperature of 25 C (10). The decreased efficiency in the cold probably resulted from increased tension and viscosity of the cold muscles and to the fact that a greater proportion of the energy involved in the work was being derived from anaerobic sources. The men were actually shivering at the time they started the runs. Asmussen (1) has found that the efficiency of anaerobic work is much lower than that of aerobic work. Although this study was not designed to evaluate the effect of a preliminary warm-up on maximal work capacity, the data of these experiments indicate that a proper warm-up should improve performance by increasing both aerobic capacity and the efficiency of work by the man. Karpovich and Hale (6) reported that a warm-up did not improve performance of men in running 440 yards, while Asmussen and Boje (2) found that a warm-up improves performance in maximal work. Of course it should be recognized that our subjects were chilled to the point of shivering in in the cold experiments and therefore might profit more from a warm-up

[redacted]

than the subjects in the other studies who were presumably comfortably warm and relaxed at the time of the tests.

Acknowledgements

The authors gratefully acknowledge the technical assistance contributed by Daniel Haynes. They also wish to thank Arthur Campbell, David Coles, George Finley, and David Lloyd for acting as subjects in these experiments.

[redacted]

References

1. Asmussen, E. Aerobic recovery after anaerobiosis in rest and work. Acta Physiol. Scand. 11: 197-210, 1946.

2. Asmussen, E. and D. Boje. Body temperature and capacity for work. Acta Physiol. Scand. 10: 1, 1945.

3. Burton, A. C. The application of theory of heat flow to the study of energy metabolism. J. Nutrition 5: 497, 1934.

4. Gisolfi, C., S. Robinson and E.S. Turrell. The effects of aerobic work performed during recovery from exhausting work. J. Applied Physiol. 21: 1767-1772, 1966.

5. Hohorst, H. J. Enzymatische Bestimmung von L(+)-Milchsäure. Biochem. Z. 328: 509, 1957.

6. Karpovich, P. V., and C. Hale. The effect of warming-up on physical performance, J.A.M.A. 162: 1117, 1956.

7. Robinson, S. Temperature regulation in exercise. Pediatrics 32: 691-702, 1963.

8. Robinson, S., and S. D. Gerking. Thermal balance of men working in severe heat. Am. J. Physiol. 149: 476-488, 1947.

9. Robinson, S., E.S. Turrell and S. D. Gerking. Physiologically equivalent conditions of air temperature and humidity. Am. J. Physiol. 143: 21-32, 1946.

10. Robinson, S., F. R. Meyer, J. L. Newton, C.H. Ts'ao, and L. O. Holgersen. Relations between sweating, cutaneous blood flow and body temperature in work. J. Applied Physiol. 20: 575-582, 1965.

11. Rowell, L. B., J. R. Blackmon, R. H. Martin, J.A. Mazzarella and R. A. Bruce. Hepatic clearance of indocyanine green in man under thermal and exercise stresses. J. Applied Physiol. 20:384-394, 1965.

12. Williams, C. G., G. A. G. Bredell, C. H. Wyndham, N. B. Strydom, J. F. Morrison, and J. Peters, P. W. Fleming and J. S. Ward. Circulatory and metabolic reactions to work in heat. J. Applied Physiol. 17: 625-638, 1962.